Trade-offs between nutrient circularity and environmental impacts in the management of organic waste

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ABSTRACT

Measuring the circularity of resources is essential to assess the performance of a circular economy. This work aims at proposing an indicator that quantifies how effective a system is at extending the lifetime of its waste components after they have been discarded. The developed indicator was applied to study the circularity of nutrients within a system that handles the organic waste (OW) generated in the Spanish region of Cantabria. A superstructure was developed to determine the optimal configuration of the system. It comprises alternative Unit Processes (UPs) for i) the management of OW, and ii) the application of the recovered products as soil amendment to grow corn. A multi-objective Mixed Integer Linear Programming problem was formulated under two policy scenarios with different source separation rates (SSRs). The problem was optimized according to six objective functions: the circularity indicators of carbon, nitrogen and phosphorus, which are maximized, and their associated environmental impacts to be minimized (global warming, marine eutrophication and freshwater eutrophication). The model was fed with the Life Cycle Assessment results obtained with EASETECH (Environmental Assessment System for Environmental TECHnologies) and the nutrient flows in the agriculture subsystem, which were calculated with DNDC (DeNitrification-DeComposition). It was concluded that improving nutrient circularity paradoxically leads to eutrophication impacts, and increasing the SSR of OW has a positive effect on the carbon footprint of the system.

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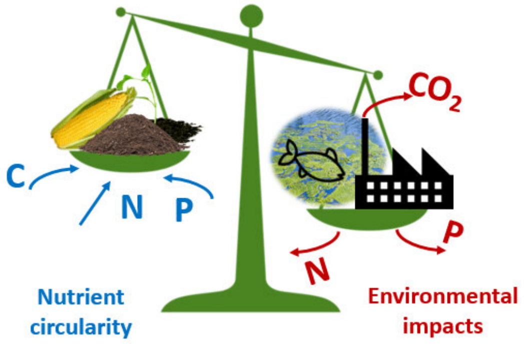


INTRODUCTION

In the context of a boom of initiatives promoting a circular economy within the European Union,[1-3] it is the responsibility of researchers to provide policy-makers with the data and tools needed to make informed decisions. Measuring the circularity of resources is key to assessing the performance of a circular economy.

Literature overview

Several approaches have been presented to tackle this challenge. One study defined a global circularity indicator as the share of material inputs into the global economy that are cycled, subsequently estimating that the global economy was 9.1% circular in 2015.[4] Although this indicator provides insight into the global materials metabolism, policy implications cannot be directly derived from it. Instead, an indicator that can be applied to systems design and operation is of more interest to the policy makers.

Some authors suggest that circularity indicators should capture how the differences between the physico-chemical properties of the recovered waste components and the primary resources they displace affect their substitution ratio.[4-7] Accordingly, Moriguchi[5] pointed out that the reduction in the requirement for primary resources could be a good indicator of circularity. However, this does not necessarily entail that more waste components are being recovered; it could be the consequence of an increase in the eco-efficiency of the system.

Haupt et al.[6] suggested that open-loop and closed-loop recycling rates that reflect the efficiency of the recycling processes and the type of application of the recycled components in their next life cycle stage should be used as performance indicators for a circular economy.

The duration of material retention within a system has also been recommended as an indicator of circularity.[7] Following this line of thinking, the Ellen MacArthur Foundation proposed the lifetime of a product as one of the parameters used to calculate its circularity indicator.[8] Although this indicator is useful for companies, it does not provide information about the circularity of the components of the product, since it does not consider their entire life cycle.

The described indicators do not correlate with the quality of the recovered components and they do not reveal how much of the recovered components are consumed again; i.e., to what extent the loop is closed.

The methodology proposed by Cobo et al.,[9] which enables to track waste components within a Circular Integrated Waste Management System (CIWMS), might help overcome these limitations, since CIWMSs encompass not only waste management, but also the processing and consumption of the components recovered from waste and the external raw materials that eventually become waste.

Case study

This framework is applied to the study of the management of organic waste (OW) in the region of Cantabria, in the north of Spain. The OW generated in Cantabria ($83.5 \cdot 10^3$ metric ton in 2014) is collected with other discarded household inorganic materials. The OW that is sorted out at the regional mechanical-biological treatment facility is subjected to a windrow composting process. Nonetheless, Directive 2008/98/EC[10] does not allow the land application of the bio-stabilized material derived from the composting of the OW separated from the mixed waste stream (mix-OW); only the OW that has been source separated (SS-OW) can be recycled. The expiration of the regional authorization that permitted the sale of the bio-stabilized material as compost until 2018[11] makes it impossible for the current waste management system to comply with the legal restraints. The need to retrofit the system represents an opportunity to implement new circularity practices. The interest of recycling OW lies in the nutrients it contains.

Implications of nutrient recovery

This study focuses on three essential nutrients to soil amendment: carbon (C), nitrogen (N) and phosphorus (P). Enhancing the circularity of these nutrients within a CIWMS *a priori* seems to be a strategy that will contribute to closing their natural biogeochemical cycles by avoiding the accumulation of nutrients in one of the Earth's subsystems (atmosphere, hydrosphere, biosphere or lithosphere) at a rate faster than the ecosystems can sustain. Thus, the relevance that a circular economy of nutrients might have to global sustainability challenges should not be underestimated. On the one hand, the forthcoming peak P production, due to the depletion of the global rock phosphate reserves, threatens future food security;[12] on the other, the anthropogenic interference with the C and N biogeochemical cycles to meet the energy and food demands has already caused the transgression of the estimated climate change and N cycle planetary boundaries within which humanity is expected to operate safely.[13]

Since the nutrient cycles interact with each other,[14] promoting the circularity of one nutrient might have consequences on the biogeochemical cycles of the others. For instance, increasing Soil Organic Carbon (SOC) stocks may exacerbate N_2O emissions,[15] and an increased availability of reactive N may lead to C sequestration because of biomass growth.[16] Another counter-effect related to the land application of the products recovered from OW is the accumulation of surplus P in agricultural soils, because the N:P ratio in organic fertilizers is lower than the N:P ratio required by crops.[17-19]

Aim of the work

The circularity of C, N and P within a CIWMS and the main impacts associated with the emissions of these elements to the environment (global warming, marine eutrophication and freshwater eutrophication) must be jointly analyzed. Although the recovery of nutrients is a subject that is drawing the attention of the scientific community,[20-24] the trade-offs between these indicators have not been systematically explored in the literature yet. Therefore, the objectives of this paper are the following:

- To propose a circularity indicator that can be applied to any non-renewable resource and accounts for the extended service of the components recovered from waste.
- To optimize the OW management system in the region of Cantabria, setting as objective functions the maximization of the circularity indicators of C, N and P, and the minimization of the global warming, marine eutrophication and freshwater eutrophication impacts.

METHODOLOGY

Material Flow Analysis (MFA), Life Cycle Assessment (LCA) and multi-objective optimization were applied to determine the optimal configuration of the Cantabrian CIWMS aiming at nutrient recovery from OW. A superstructure comprising the combinations of unit processes (UPs) that could emerge as a result of the optimization was proposed, as shown in Figure 1. The UPs that already belong to the Cantabrian waste management system are represented with a discontinuous line.

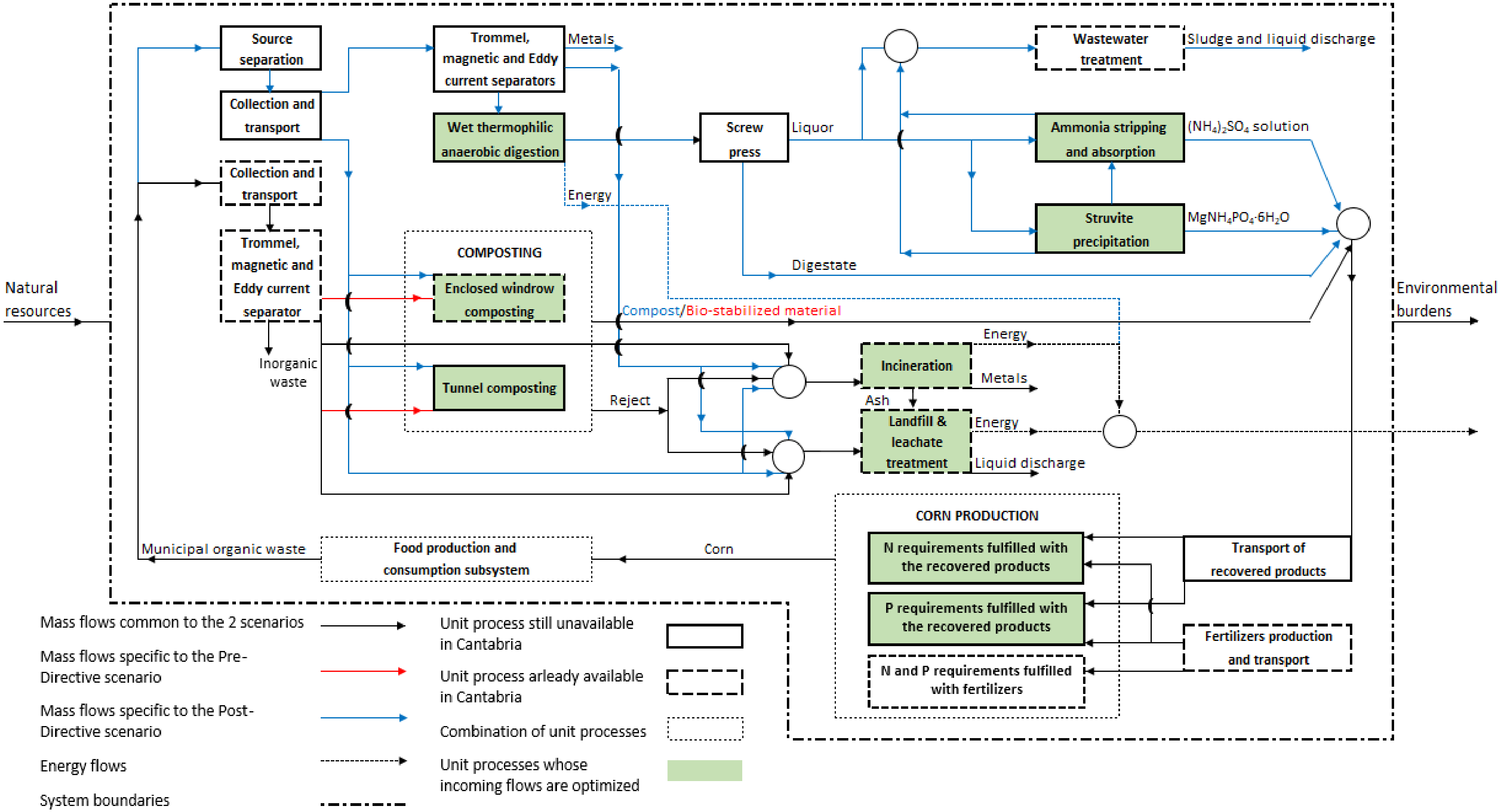


Figure 1. Studied CIWMS

Superstructure description

The products recovered from OW were assumed to be applied to land to grow corn, the main fodder crop grown in Cantabria.[25] The superstructure comprises a set *j* of UPs for the management of OW and a set *k* of corn production UPs. The UPs that can handle the solid OW are wet thermophilic anaerobic digestion, windrow composting inside an enclosed building, composting inside a tunnel reactor, incineration and landfill. The ammonia stripping and absorption and the struvite precipitation UPs recover nutrients from the liquid digestate (LD) produced in the anaerobic digestion, which only processes SS-OW after it has been pretreated.[26-30] The remaining liquor is sent to a wastewater treatment plant. Incineration and landfill can also handle the rejects generated by the other UPs. It is assumed that all the waste processing units are in the same facility. A detailed description of these UPs can be found in Cobo et al.[31]

The nutrient uptake efficiencies of corn (shown in Appendix D of the Supporting Information) differ for each type of applied product (bio-stabilized material, compost, digestate, struvite and ammonium sulphate). As shown in Appendix C of the Supporting Information, P is in excess with respect to the amount of N required by corn in all the recovered products except for ammonium sulphate. Consequently, the nutrient flows were modeled so that the optimal approach to corn production can be either based on one of these strategies or on a combination of them:

S1) Application of the amount of recovered product needed to cover the corn N requirements. Unless ammonium sulphate is recovered, excess P is applied to soil, leading to freshwater eutrophication.

S2) Application of the amount of recovered product needed to cover the corn P requirements. The N requirements are fulfilled with an industrial fertilizer (NH_4NO_3).

S3) Application of industrial N and P fertilizers (NH_4NO_3 and $(NH4)_2HPO_4$).

The alternative combinations of the corn production UPs that can arise from the application of these strategies are shown in Figure 2. The N and P requirements of corn are defined as the amounts of these nutrients that yield the maximum average annual crop production that can be achieved in a 100-year timeframe with industrial N and P fertilizers. Assuming an 80% collection rate of the produced corn grain, it corresponds to a net production of 7.11 tons of corn grain per ha per year.

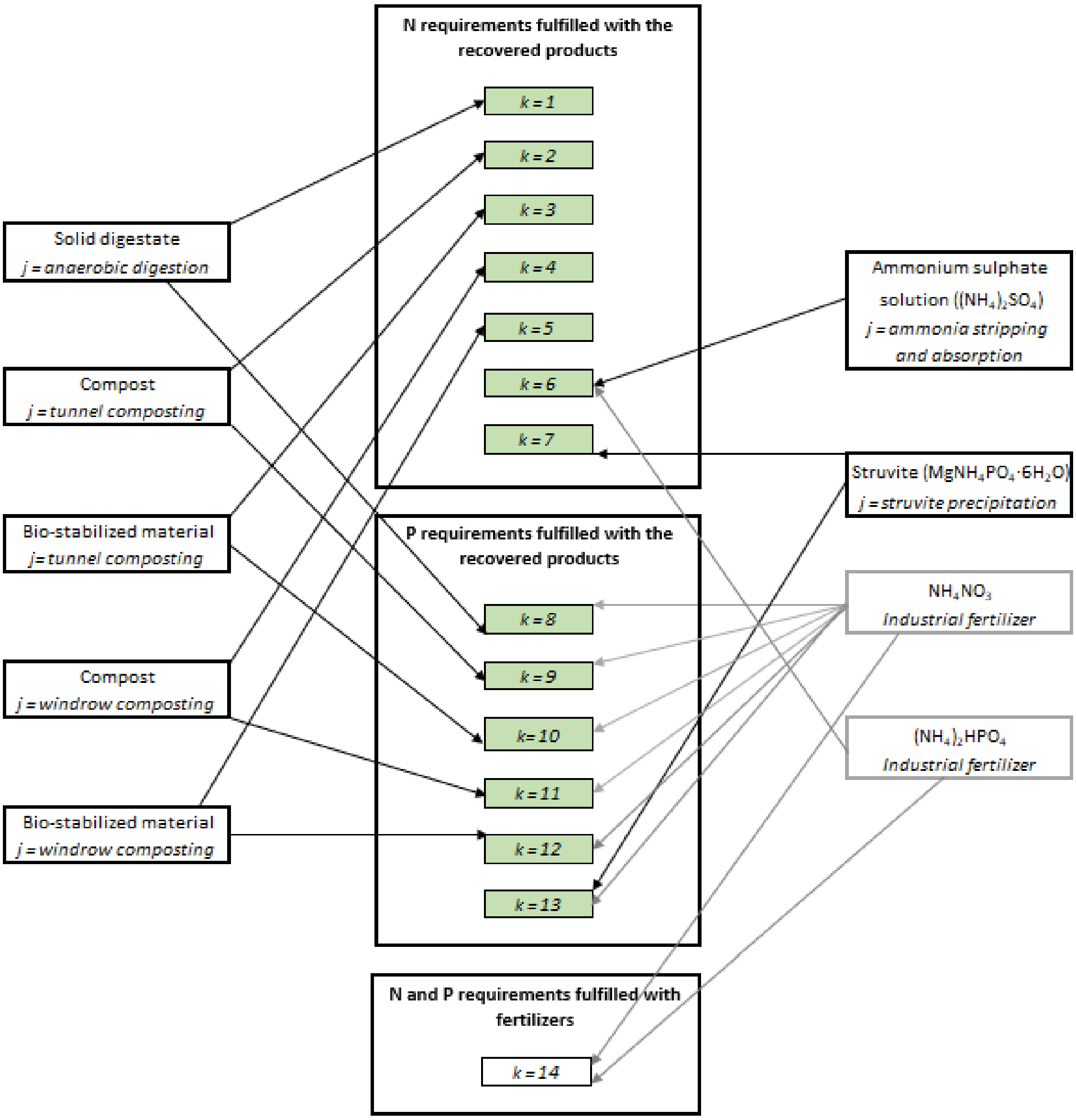


Figure 2. Possible combinations of inputs to the corn production subsystem

Data flow

A modular LCA approach, where the LCA of the individual UPs of the system is carried out,[32,33] was performed. The UPs concerning the management of solid OW were modeled with EASETECH 2.3.6,[34] which provided their environmental impacts. The nitrate and phosphate leachate, the emissions of CO_2, N_2O and NO, the amount of Dissolved Organic Carbon (DOC) consumed by soil microorganisms, the flows of N and P uptaken by corn and the amount of nutrients stored in soil per hectare of cultivated corn were calculated with DNDC 9.5.[35] These results were transferred to EASETECH 2.3.6, where the environmental impacts associated with the land application of the recovered products and corn production were calculated.

The results obtained with DNDC and EASETECH were exported as parameters to GAMS (General Algebraic Modeling System) 24.8.1, where the problem was formulated. Figure 3 clarifies the data flows derived from the application of this methodology.

The data required to characterize the UPs that integrate the system are compiled in the Supporting Information: waste composition (Appendix A), waste management UPs (Appendix B) and corn production subsystem (Appendix C).

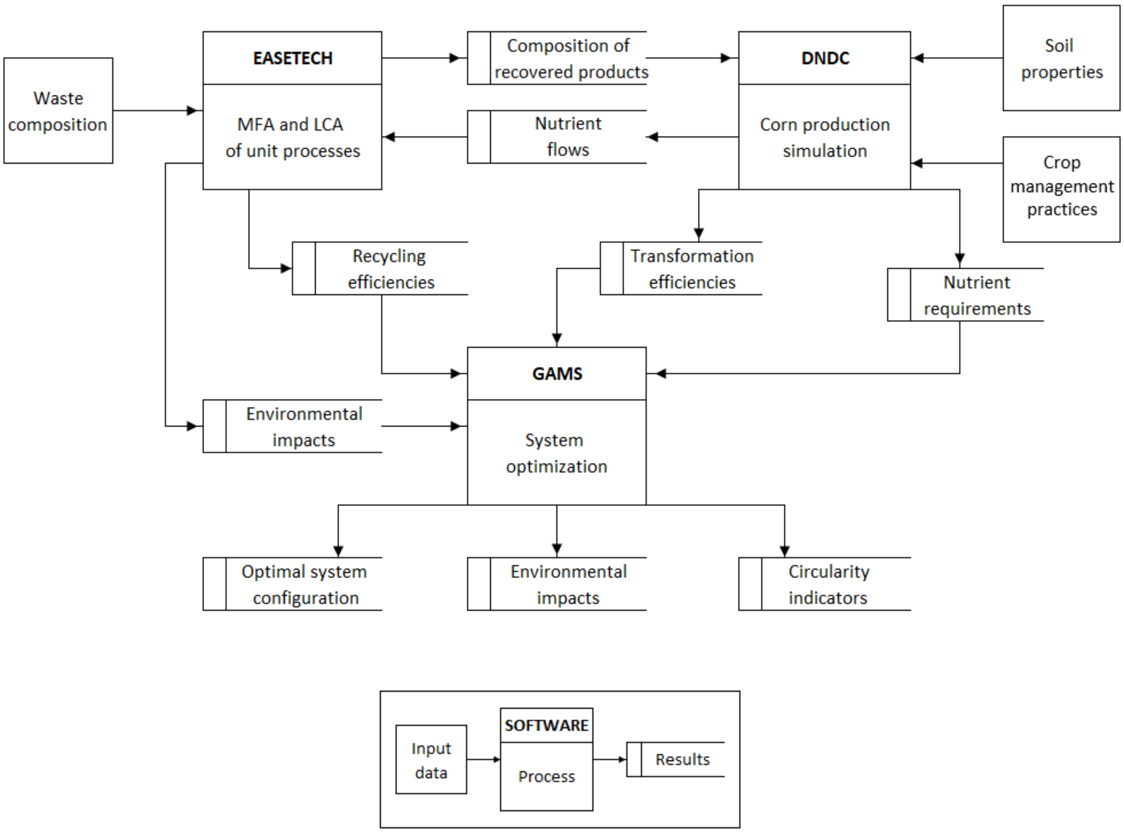


Figure 3. Data flow diagram

DEFINITION OF THE CIRCULARITY INDICATORS

Figure 4 illustrates the flows of the component *i* of a given waste stream within a CIWMS. The circularity indicator of component *i* (CI_i) is defined as the amount of component *i* that extends its lifetime by providing a service in the upstream processes with respect to the amount of that component present in the collected waste. Equation 1 shows how the CI_i is calculated for a set of *n* recycling and preparation for reuse processes and *m* production processes that valorize this component.

$$CI_i = \frac{\sum_{k=1}^{m} \sum_{j=1}^{n} R_{ijk} \cdot \eta_{r_{ij}} \cdot \eta_{p_{ik}}}{W_i} \tag{1}$$

The variables needed for the calculation of CI_i are these:

- W_i. Amount of component *i* present in the waste stream (kg).
- R_{ijk}. Amount of component *i* that enters the recycling or preparation for reuse process *j*. The subsequently recovered component *i* enters the production process *k* (kg).
- $\eta_{r_{ij}}$. Efficiency of the recycling or preparation for reuse process *j* for component *i* (kg of component *i* recovered per kg of component *i* that enters process *j*).
- $\eta_{p_{ik}}$. Efficiency of the production process *k* at transforming or incorporating the recovered component *i* into a product that will deliver a service in the consumption subsystem (kg of component *i* transformed per kg of component *i* that enters process *k*).

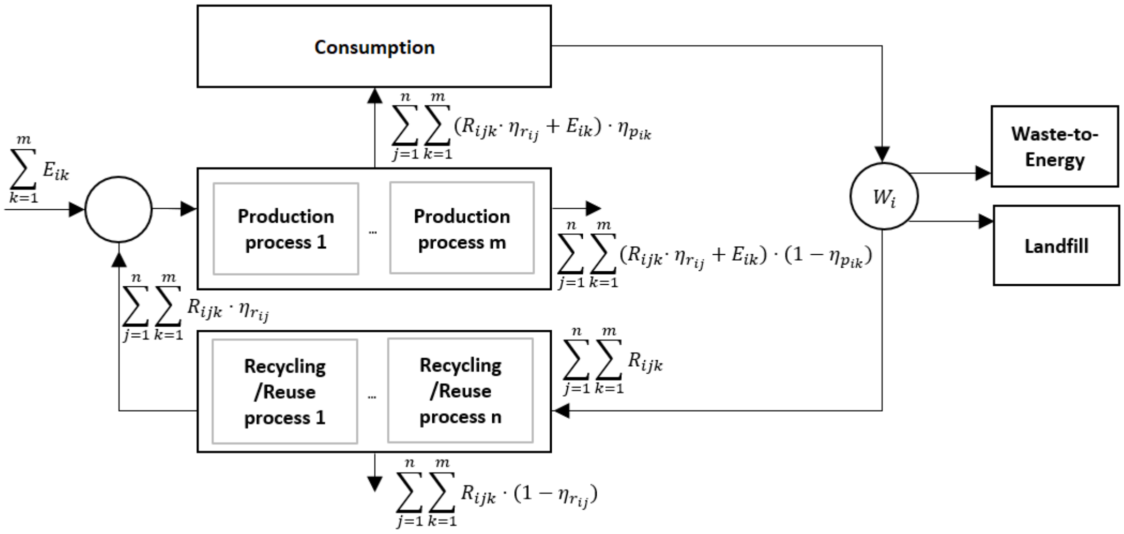


Figure 4. Simplified CIWMS

CI_i is dimensionless, its value can range between 0 and 1. A value of 1 implies that the total amount of component *i* that was discarded is recovered and reprocessed to enter the consumption subsystem, indicating that there are not any losses of component *i* in the recycling, preparation for reuse and upstream processes. If $CI_i = 0$, component *i* is not recovered at all, but incinerated or landfilled instead.

The proposed indicator indirectly accounts for the quality of the recovered components by quantifying how much of the recovered component is consumed. This indicator does not account *per se* for the degradation of the waste components after successive cycles, but if the selected time horizon of the study is wide enough, a dynamic analysis should show how for a sustained service demand, the external supply of component *i* ($\sum_{k=1}^{m} E_{ik}$) must increase due to the degradation of the recovered component.

Nutrient circularity indicators

The circularity indicators of N and P (CI_N and CI_P) were defined as the amount of nutrient *i* that is recycled, applied to land and uptaken by corn with respect to the amount of nutrient *i* present in the collected OW.

The same definition cannot be applied to the C circularity indicator (CI_C), since the C captured by vegetation in the photosynthesis process does not come from the soil but from the atmosphere.

Besides improving the water-holding capacity of soil and its ability to retain cations in a plant available form, contributing to C sequestration and promoting the formation of soil structure,[36,37] the purpose of applying a source of C to land is to feed the soil microorganisms. When these microorganisms decompose the SOC, the decomposed C is partially lost as CO_2, and DOC is produced as an intermediate that can be consumed by the soil microorganisms.[38] These microbes are also responsible for the N fixation, ammonification and nitrification processes that release N compounds that plants can assimilate; they are essential for crop production.

Consequently, a different definition was proposed for CI_C. It was defined as the ratio between the mass of DOC that is recycled, applied to land and consumed by microbes with respect to the amount of C present in the collected waste.

The values of $\eta_{r_{ij}}$ and $\eta_{p_{ik}}$ required for the calculation of the circularity indicators are compiled in Appendix D of the Supporting Information.

PROBLEM FORMULATION

A single-period Mixed Integer Linear Programming problem was formulated for the optimization of the decision variables; i.e., the incoming material flows (waste and recovered products) to the green shaded UPs in Figure 1. The problem was optimized according to these objective functions, where x and y represent the continuous and binary variables respectively: the circularity indicators of the studied nutrients, which must be maximized ($CI_C(x,y)$, $CI_N(x,y)$, and $CI_P(x,y)$), and the selected environmental impacts of the system to be minimized (global warming $GW(x,y)$, marine eutrophication $MEU(x,y)$ and freshwater eutrophication $FWE(x,y)$).

After verifying the trade-offs between the objective functions, a multi-objective problem was formulated as follows:

$$\min U(x,y) = \{GW(x,y), MEU(x,y), -CI_N(x,y), -CI_P(x,y)\} \;\; s.t. \;\; \begin{cases} h(x,y) = 0 \\ g(x,y) \leq 0 \\ x \in \Re^n \\ y \in \{0,1\}^m \end{cases} \qquad (2)$$

The equations that describe the behavior of the system ($h(x,y) = 0$) are based on the mass balances of the UPs. The problem is subjected to these restrictions ($g(x,y) \leq 0$):

- The area fertilized with the recovered products cannot exceed the available area to grow corn in Cantabria (4810 ha).[39]
- The amount of biodegradable waste sent to landfill must be lower than 35% of the domestic waste generated in 1995 (170,168 ton),[11] as established by Directive 1999/31/EC.[40]
- Windrow and tunnel composting cannot accept waste streams with the same composition.
- SS-OW and mix-OW cannot be mixed in any composting processes.

The GAMS model comprises a total of 844 equations, 19 inequations, 817 continuous variables and 28 discrete variables. The main input parameters to the models are the source separation rate (SSR), the total area available for corn production and the amount of OW generated yearly in Cantabria.

Different waste collection systems for SS-OW and commingled waste were modeled. It was considered that the composition of SS-OW is 98% OW and 2% impurities, which is consistent with documented source separation experiences.[41] Two scenarios (neglecting and considering the current legislative framework) were analyzed:

- **Pre-Directive scenario.** Mix-OW can be recycled. The SSR is 0% and no recycling target is set. The red arrows in Figure 1 represent the flows of mix-OW that can only be composted in this scenario.
- **Post-Directive scenario.** Mix-OW cannot be recycled. To comply with the 50% OW recycling target established by the Cantabrian waste management plan[11] for 2020, a 50% SSR is set, and an additional restriction is added to the model to ensure that 50% of the collected OW is composted or anaerobically digested. The blue arrows in Figure 1 represent the flows of SS-OW that are specific to this scenario.

The multi-objective optimization problem was solved with the CPLEX solver and the Ɛ-constraint method.[42]

MODELING APPROACH AND ASSUMPTIONS

The boundary that separates the studied CIWMS from the ecosphere (which provides the natural resources consumed by the system and a sink for the generated environmental burdens) and the rest of the technosphere is depicted in Figure 1.

Although crops are managed by farmers under controlled conditions in the technosphere, they produce natural biotic resources. Hence, the boundary between technosphere and ecosphere is difficult to identify for agricultural soils.[43] One of the strategies recommended by Notarnicola et al.[44] to overcome the limitations of considering agricultural soils as part of the technosphere, is to include the impacts of crop production on soil. In this study the land application of the recovered products and the production of corn were modeled as a UP. Although the system was optimized for 1 year of operation, the selected 100-year time horizon enabled to account for the loss of soil quality due to soil nutrient depletion caused by the production of consecutive annual crops. The average annual corn production and emission rates in that timeframe were considered.

Corn enters the food production and consumption subsystem, which comprises the upstream processes that transform corn and the other food commodities consumed in Cantabria into OW. It composes the background subsystem of the CIWMS because its configuration does not affect the results of the study;[45] only the flows and the composition of its inputs and outputs (corn and waste) that connect it to other UPs are calculated.

According to Cobo et al.,[9] the primary function of CIWMSs is to recover waste components so that their service life in the upstream processes can be extended. In this case study the elements recovered from OW are used for land fertilization and soil conditioning. Since the studied CIWMS encompasses the entire corn production of the region, the functional unit selected to perform the LCA of the system is defined as the area available to grow corn in Cantabria (4810 ha).[39]

An attributional LCA approach was applied. The electricity generated at incineration, anaerobic digestion and landfill is considered the secondary system function. The direct substitution method was applied by expanding the system boundaries to include the generation of electricity from the Spanish grid mix. A 100% substitution ratio was assumed.

The characterization factors of each emission were calculated with the hierarchical 100-year perspective of the ReCiPe 1.11 method. The assumptions made by the DNDC model about the distribution of nutrients in the environment can be found in Li et al.[46] Following the rationale explained by Cobo et al.,[9,31] only the biogenic C present in animal and vegetable food waste (which can i) leach into the water, ii) be emitted to the atmosphere, or iii) be stored either in the landfill or the soil as a result of the land application of the recovered products, as shown in Appendix C of the Supporting Information) was considered neutral. The CO_2 derived from the decomposition of SOC was also quantified as fossil C.

Regarding the limitations of the model, the environmental impacts related to capital goods were excluded from the analysis. Moreover, this work assumes that all the P is in mineral form and accessible for plants. Studies have shown that most of the P in the products recovered from OW is in mineral form, but not all of it.[47-50]

On the contrary, the mineralization of organic N is quantified by the DNDC biogeochemical model. The organic/inorganic N ratio was assumed to be 93/7 for the compost and bio-stabilized material,[50] and 62.96/37.04 for the solid digestate.[51]

The DNDC model assumes a 60% microbial efficiency to calculate the amount of C incorporated into microbial biomass in amended soils, defined as the ratio of C assimilated into microbial biomass to residue C released by decomposition.[46]

RESULTS AND DISCUSSION

The results of the problem optimization determine the system configuration; i.e., the UPs that the system comprises and their incoming flows of waste and recovered products. The values of the objective functions and the decision variables that optimize each objective function for the two studied scenarios are compiled in Figure 5. Figure 5A shows the optimal flows of OW and LD handled by the *j* UPs. The optimal flows of the recovered products into the *k* corn production UPs (Figure 5B) are shown along with the area fertilized with the recovered products. The contribution of the UPs to the environmental impacts of the optimal system configurations of each scenario are depicted in Figure 6.

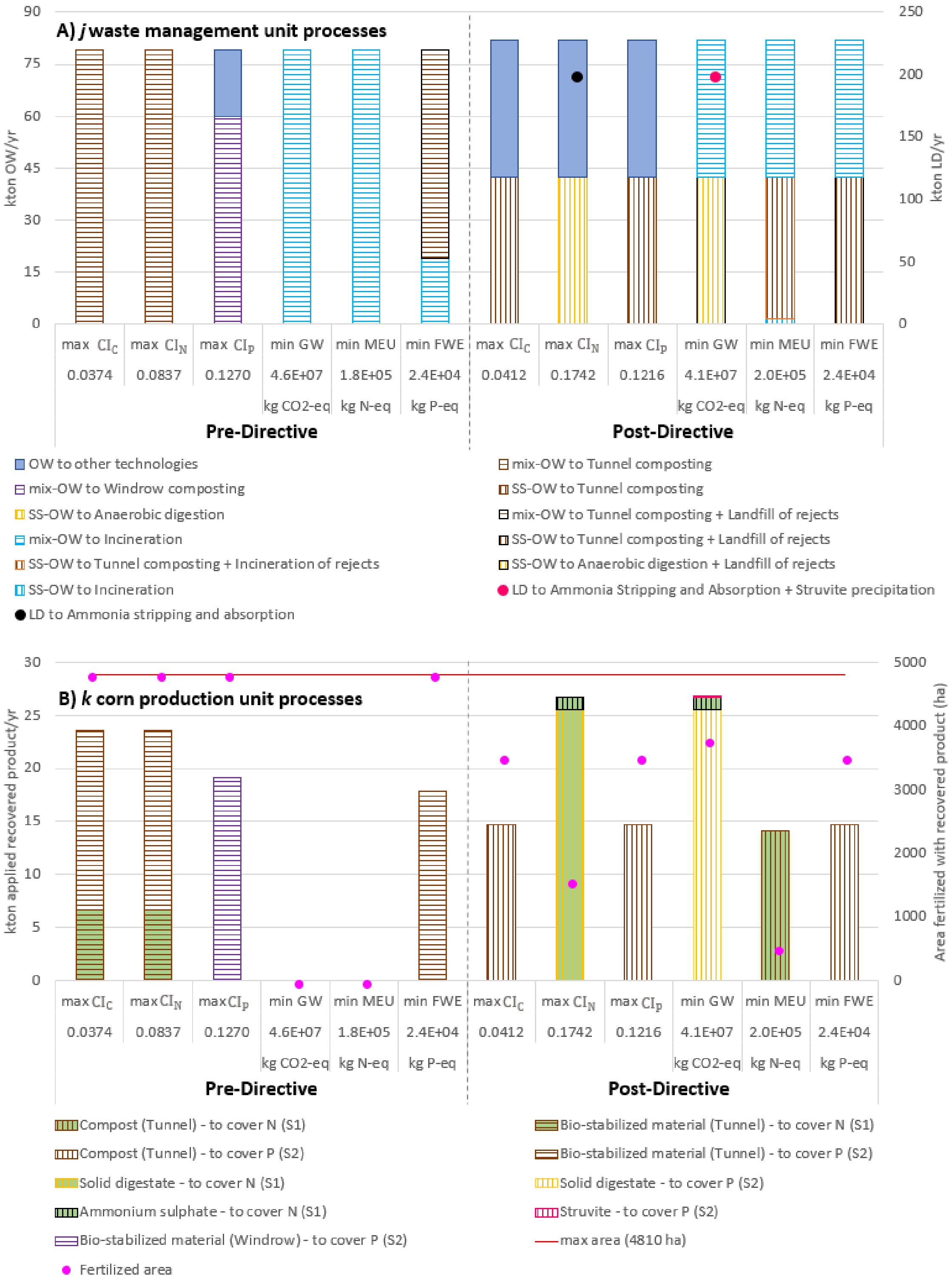


Figure 5. Values of the objective functions and decision variables for the optimization of the Pre-Directive and Post-Directive scenarios

The flows of OW shown in Figure 5A are lower in the Pre-Directive scenario because part of the OW present in the mixed waste ends up in the inorganic waste stream after the trommel separation required for the pretreatment of mixed waste.

There are several system configurations that lead to the maximization of a given circularity indicator, because the UPs that manage the rejects do not affect the corn production subsystem, and thus they do not contribute to closing the nutrient loops. By analogy, in the Post-Directive scenario where mix-OW cannot be recycled, the selection of any UP for its management will result in the same circularity indicators. This is the reason the maximization of the circularity indicators in Figure 5A only shows the UPs that contribute to recirculate nutrients.

The amount of P present in the mix-OW collected in the Pre-Directive scenario is more than enough to cover the P requirements of the corn produced in Cantabria under the hypothesis of this work. However, the N present in OW cannot fertilize all the land available for corn production in any of the studied scenarios. Consequently, strategies S1 and S2 must be combined in the Pre-Directive scenario to maximize CI_C and CI_N. As Figure 5B shows, more area is fertilized with the recovered products in the Pre-Directive scenario because of the higher amount of OW that can be recycled, which makes farmers less dependent on industrial fertilizers (strategy S3). Oppositely, the optimization of all the objective functions are partially based on strategy S3 in the Post-Directive scenario.

The optimization of some objective functions provides duplicate or very similar results (freshwater eutrophication and CI_P on the one hand, CI_C and different circularity indicators in each scenario on the other). To avoid redundant results, freshwater eutrophication and CI_C were not considered in the next part of the study, focused on a multi-objective optimization of the other four objective functions.

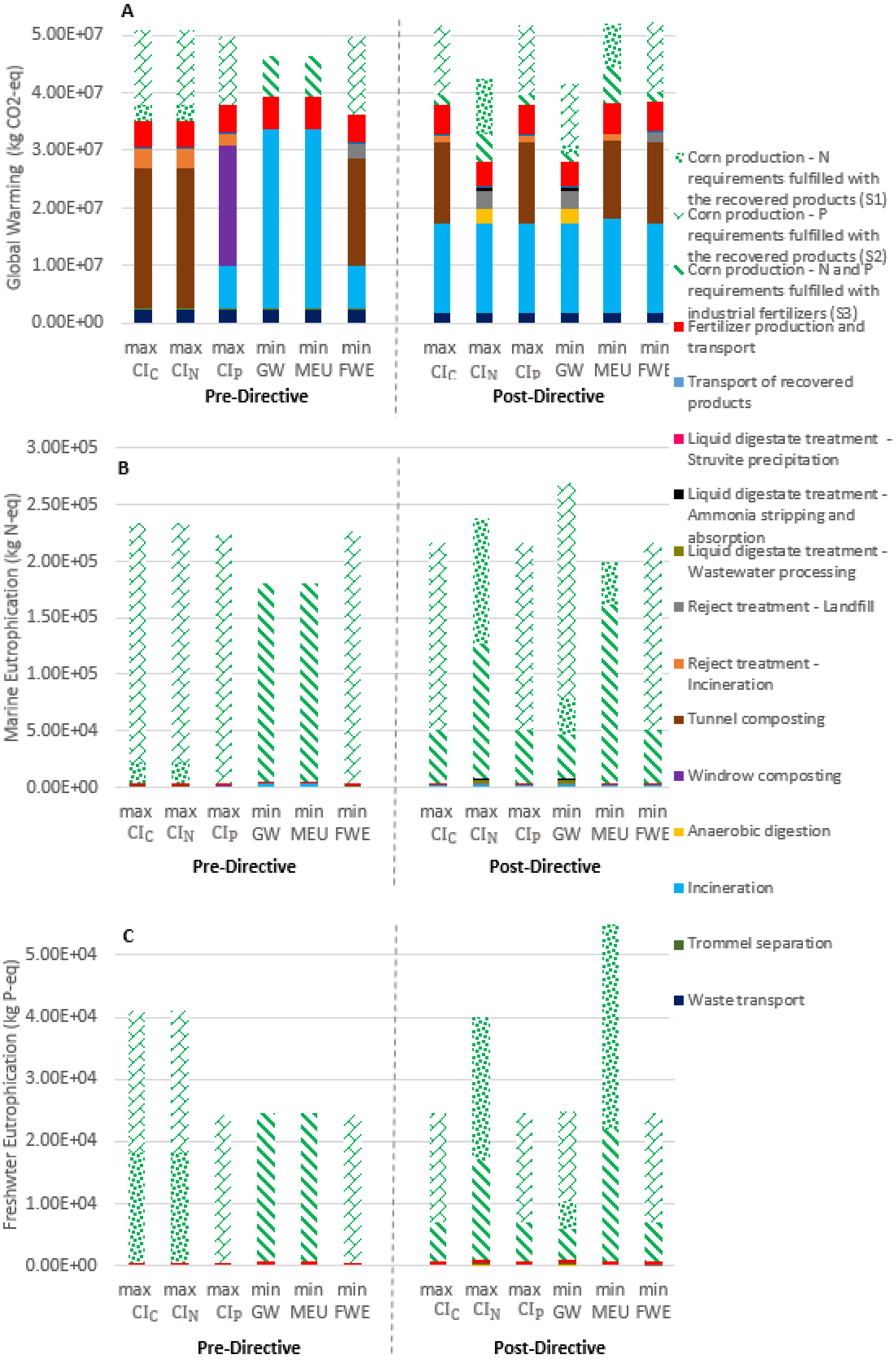


Figure 6. Contribution of the UPs to the environmental impacts in the Pre-Directive and Post-Directive scenarios

Figure 7 shows the Pareto fronts of the two scenarios, where each point is better than the others in at least one of the values of the objective functions. Global warming and marine eutrophication are normalized with respect to the maximum value of the two scenarios.

As the results of the DNDC simulations show, if industrial fertilizers, ammonium sulphate or struvite (inorganic fertilizers) are exclusively applied to soil, the corn Nitrogen Use Efficiency (NUE, defined as the fraction of N input harvested as product)[52] decays over time because of the depletion of SOC. The opposite occurs when bio-stabilized material, compost and digestate (organic fertilizers) are applied, due to their C rich composition. However, the mean NUE obtained for the 100-year time horizon if inorganic fertilizers are applied to land is higher than the NUE achieved after the soil application of the organic fertilzers, because the share of plant available inorganic N in the latter is low. This implies that more N leaches when the organic fertilizers with a high organic N content are applied to land. These results are supported by previous studies that highlight that the N leaching rate of organic fertilzers is higher than that of inorganic fertilizers.[53,54]

As Figures 6B and 6C indicate, the corn production subsystem is the main contributor to the eutrophication impacts. In both scenarios the marine eutrophication impacts increase with the CI_N, being the values of these two objective functions higher in the Post-Directive scenario. A similar correlation cannot be established between CI_P and freshwater eutrophication because, unlike N, which tends to leach as nitrate when it is applied to soil, P is strongly sorbed onto soil particles; in fact its major environmental losses can be attributed to erosion.[55]

The Pre-Directive scenario, where the minimum amount of OW that must be recycled is not restricted, relies on incineration and the application of industrial fertilizers. Figure 6A shows that, although the production of industrial fertilizers is very energy intensive,[56] the carbon footprint associated with their land application is lower than that of the organic fertilizers, a fraction of which degrades to CO_2 after their land application. Thus, as Figure 7A shows, in the Pre-Directive scenario as CI_N increases, the CO_2-eq emissions increase too.

Anaerobic digestion is the UP that handles OW with the lowest carbon footprint. Hence, the minimum carbon footprint achieved at the Post-Directive scenario, the only one where SS-OW can be subjected to anaerobic digestion, is lower than in the Pre-Directive scenario. Moreover, since the N recycling efficiency of anaerobic digestion and the LD UPs is higher than that of the other UPs, the land application of the products derived from anaerobic digestion also maximizes CI_N. Therefore, as shown in Figure 7B, in the Post-Directive scenario as the CI_N increases, the carbon footprint of the system decreases.

Regarding CI_P, it shows a similar trend to the CI_N in the Pre-Directive scenario, whereas no clear trend can be appreciated in the Post-Directive scenario, where the maximimization of CI_P is based on the application of compost to cover the soil P requirements, and the maximization of CI_N on the application of ammonium sulphate and solid digestate to fulfill the soil N needs, which leads to the accumulation of P in soil. The values of CI_P are lower in the Post-Directive scenario because of the restriction that prevents mix-OW from being recycled.

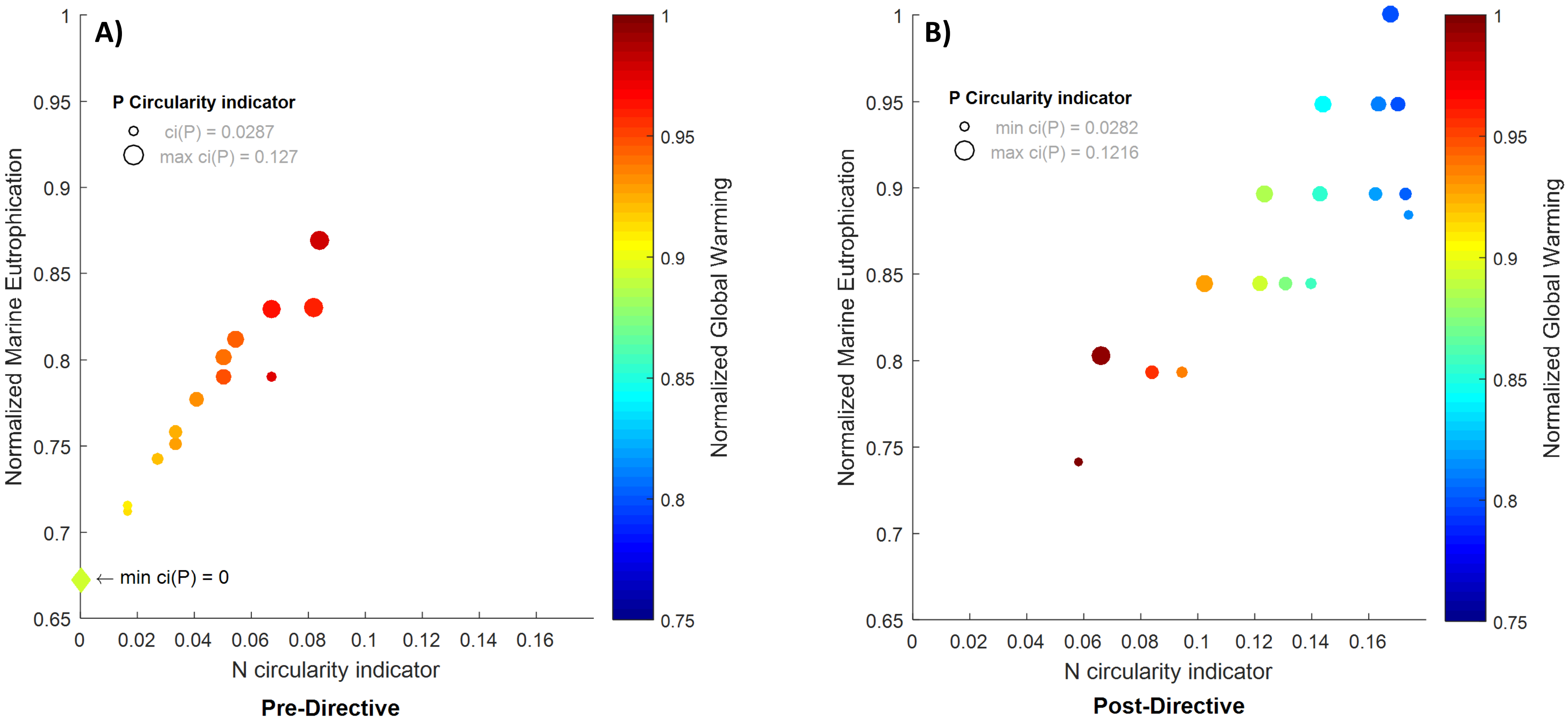
A sensitivity analysis was performed to ascertain the consequences that a 20% decrease in the values of two key parameters have on the results. The Spanish legislation prioritizes electricity from the biogas produced at landfills and anaerobic digestion facilities over other sources of non-renewable electricity. Notwithstanding, the electricity generated from waste incineration does not have priority access to the grid.[57] The sensitivity analysis considered that 80% of the electricity generated from the incineration of OW replaced the electricity from the Spanish grid mix. On the other hand, it is hard to estimate the composition of SS-OW, since pilot experiments for the source separation of OW have not been carried out in Cantabria. The sensitivity analysis assumed that the fraction of OW in the SS-OW was 78.4%.

The results of the single-objective optimization of each scenario under the conditions of the uncertainty analysis are compiled in Appendix E of the Supporting Information. The main difference in the values of the decision variables after the performance of the sensitivity analysis is that the freshwater eutrophication impacts of incineration exceed those of landfill. Thus, landfill is selected over incineration when the freshwater eutrophication impacts are minimized. As expected, the results of the sensitivity analysis led to slightly higher environmental impacts in both scenarios and lower circularity indicators in the Post-Directive scenario.

Figure 7 proves that the environmental impacts associated with increasing the circularity of nutrients cannot be overlooked. Whereas in the pre-Directive scenario there is a clear opposite trend between the environmental impacts and the circularity of nutrients, the behavior of the system in the Post-Directive scenario, subject to more restrictions and with more available UPs, is more complex.

The findings of this study suggest that increasing the SSR of OW leads to a reduction in the carbon footprint of the system. Although the results indicate that increasing the circularity of N has detrimental eutrophication impacts, these are highly dependent on the sensitivity of the receiving environment;[58] thus general conclusions cannot be drawn.

Before selecting a system configuration that meets the sustainability concerns and satisfies the interests of all the stakeholders involved in waste management and the purchase of the recovered products, a trade-off between the studied indicators must be identified. Moreover, additional impact categories that quantify the environmental impacts associated with the presence of heavy metals or organic pollutants in the recovered products, such as human toxicity or ecotoxicity, should be included in the analysis. However, the feasibility of any system configuration cannot be demonstrated until an economic analysis is performed.



Pre-Directive

Post-Directive

Figure 7. Pareto points for the Pre-Directive and Post-Directive scenarios

NOMENCLATURE

C – Carbon
CI_C – Carbon circularity indicator
CI_N – Nitrogen circularity indicator
CI_P – Phosphorus circularity indicator
CIWMS – Circular Integrated Waste Management System
DOC – Dissolved Organic Carbon
LCA – Life Cycle Assessment
LD – Liquid digestate
MFA – Material Flow Analysis
mix-OW – Organic waste separated from the mixed waste stream
N – Nitrogen
NUE – Nitrogen Use Efficiency
OW – Organic waste
P – Phosphorus
SOC – Soil Organic Carbon
SSR – Source Separation Rate
SS-OW – Source separated organic waste
UP – Unit Process

SUPPORTING INFORMATION

Waste composition, model data, sensitivity analysis.

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